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Design, development, testing and evaluation of an innovative floating hydro-generator

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Abstract

Undershot waterwheels have existed for centuries with most designs using radially extending paddles. This work involves developing and testing prototype of a newly designed floating undershot waterwheel with a unique paddle-shaft linkage mechanism that increases the power transmission and efficiency. The prototype was tested in two different field trials: (i) a swimming pool with jets of water to replicate low-flow conditions and (ii) a millstream to replicate normal flow conditions to experimentally measure the mechanical power outputs. The experiments proved that the device was functioning with an efficiency of 55-69%, which is close to the best performances for undershot water wheels recorded in literature. The floating design of the water wheel also allows aquatics to move freely under the wheel and does not require disruptive construction of barrages or other permanent structures. The findings from this study will be useful to further optimise the current design and target even higher efficiencies.

Keywords: Hydropower, water wheels, power generation

1.Introduction

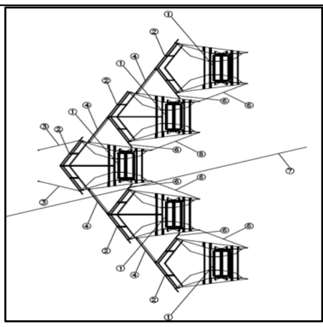
Waterwheels have been a lucrative technology used to harness the kinetic energy of the flowing water (such as small rivers, pluvial drainage systems, wastewater treatment plants, water supply systems and irrigation channels) into mechanical work and electrical power [1, 2, 3]. Until the 20th Century, wood was the most common material for making the blades of waterwheels, which made the fabrication difficult, and the durability poor. Consequently, waterwheels had a very simple design with low efficiency and apparently, little scope for improvement [2]. Thereafter, due to developments in hydraulic engineering, progress in material science, advancement of sophisticated computerised numerical control (CNC) production machines and the availability of computer aided design CAD and computer aided manufacturing CAM tools, the size, shape, design, efficiency and output power generation of waterwheels have considerably improved [4]. Several numerical and experimental methods were developed by many researchers to estimate the optimal design parameters, which can enhance the power generation using a micro hydropower [4, 5, 6]. Khan et al. [4] suggested that the undershot floating waterwheels are advantageous over the fixed undershot wheels and can be further used to develop power in the Pico range. Later, Emanuele and Roberto [7] examined that by changing the blade's shape of existing wheels to circular profile, the performance could be improved by approximately 4 %. In most of the studies and designs, the paddles are radially attached to the wheel.

In this work, a prototype of an undershot water-wheel floating generator (F-Gen) was developed using an innovative linkage mechanism to maximise power transmission and efficiency. The prototype was tested in two different field trials, namely, in a swimming pool with jets of water in order to test the device in low flow conditions and in a millstream under normal flow conditions. The performance of the F-Gen was evaluated through experiments and computational models for generating power from a small irrigation millstream.

2.Methodology

Design of the F-Gen

Figures 1 shows the F-Gen with four paddles, each 1.75 m wide and 3 m in diameter with an area of 0.9616 m^2. The paddles are circular-arc shaped and made of aluminium. The angular distance between the paddles is $2\pi/n$ where n is the total number of paddles. In the design, the position of the paddles is always normal to the water flow while entering, leaving or any time in between, thereby extracting maximum kinetic energy from the water flow. Due to its floating design, the F-Gen's installation, operation and maintenance are not disruptive to the environment as fish can pass under it. The F-Gen could be placed in a water stream requiring almost no other facilities such as training walls and penstock. It can be installed in any place with a water current without requiring construction of weirs or other large structures. The floating generator does not require a diversion of the water. Instead, there is only a temporary slowing down of the water flow under the impeller. In the case of flooding or abnormally high flow conditions, actuators can be used to alter the paddle angle to minimise the drag from the paddles. Also, the generator does not require scaling-up in case of water streams. Especially in case of wider but shallow streams, a bigger generator would be impossible to use as its wheels may strike the bed of the millstream. Instead, a number of these generators could be used in a parallel arrangement, fastened to each other and floating on the water surface (Figure 2).

	
Figure 1: F-Gen hydro generator with vertical paddles.	*Figure 2: Top view of a parallel arrangement of the F-Gen generator for wide waterways.*

Swimming pool experiments

An indoor swimming pool with two symmetrical water jets positioned under the water surface, shown in Figure 3, was selected for the trials. These two water jets were the only source of input power for driving the F-Gen paddles. The power available to the paddles (input power) was estimated by measuring the flow velocity and the volumetric flow rate of water at the outlet of the jets. Since the paddles were situated some distance away from the underwater jets, the power available to the F-Gen paddles would consequentially decrease as the jets diffuse into the water.

Figure 3: Jets of water in the pool for driving the hydro generator.

The accurate measurement of the input power available to the paddles was not possible experimentally and therefore computational fluid dynamics (CFD) simulations were used to estimate it at fixed distances from the jets. The output power from the F-Gen was measured using a pulley and weight mechanism, shown in Figure 4a. To estimate the power output, the time to lift the bucket of known weight over a height of 1 m was recorded. This process was repeated by positioning the F-Gen at different distances from the jets. A schematic of the distances of the paddle's positions from the water jets is shown in the Figure 4b. The x1 and x2 represent the positions of the paddles when they begin to enter water and when they are fully inside the water respectively. The following equation was used to estimate the output power generated by F-Gen.

$$P_o = w\frac{\Delta h}{\Delta t} \qquad \text{Eq 1}$$

Where w is gross weight of the load lifted, Δh is height through which the weight is lifted and Δt is time for lifting the load.

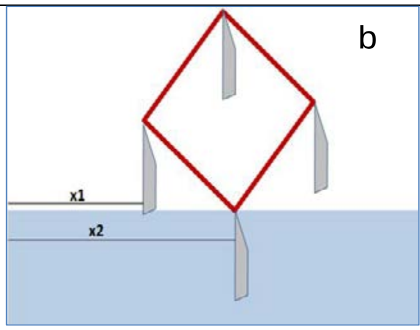


Figure 4: (a) The pulley mechanism with bucket; (b) Schematic of the distances of the paddle positions from the jets.

Millstream

In millstream trials (Figure 5), the F-Gen was subjected to a steady water velocity of 0.63 m/s.

Figure 5: Millstream setup with constant water flow and longer string to lift weights.

Hence, the power input to the F-Gen was determined experimentally by measuring the area swept by the generator and the velocity of the stream as follows:

$$P_i = \frac{\rho A u^3}{2} \qquad \text{Eq 2}$$

Where ρ is density of water, A is Area of the paddle normal to water flow and u is speed of water. The pulley mechanism described in section 2.3.1 was used to assess the output power.

3.Results and discussions

Swimming pool experiments

The output power of the F-Gen model was estimated by the pulley mechanism explained in section 2.2. The observations indicate that an average of 4.47±0.21 s was required to lift the load of 7 kg by a height of 0.25 m. The average speed of lifting is thus 0.0572 m/s. The observations and findings from the swimming pool experiments are given in Table 1. The maximum power produced by the F-Gen was found to be 3.7 W. A maximum efficiency of 69.7 % was observed, which was an encouraging sign. The aim of this experiment was solely to determine the efficiency of the F-Gen at lower flow velocities. The experiment indicates that a full-scale model of the F-Gen can produce higher power suitable for practical applications. It was observed that the efficiency of F-Gen increased as the paddles were pushed away from the jets. This increase in the efficiency was not the expected result but it can be explained as follows. The entire flux of the jets was covered by the paddles as they move away from the jets. When they were too close, some of the flow escaped without engaging the paddles.

Table 5: Power and efficiency results from Swimming pool experiments.

Parameters	Unit	Test A	Test B	Test C
x1	m	0.605	1.105	1.605
x2	m	1.450	1.950	2.450
Average lifting speed	ms^{-1}	0.0536	0.0541	0.0605
Water speed	ms^{-1}	0.270	0.251	0.224
Area of paddles	m^2	0.713	0.713	0.713
Output Power	W	3.680	3.714	3.365
Water Power available	W	7.037	5.653	4.836
Efficiency	%	52.3	65.7	69.7

Millstream experiments

The power and efficiencies observed in the millstream experiments are summarised in Table 7. The maximum power obtained in the millstream experiments is 55 W with an efficiency of 62.1%, which is 7.6 % lower as compared to the swimming pool experiments. For validation purpose, efficiencies of the F-Gen from both the experiments were compared with results reported by Ikeda et al. [8] for undershot water wheels. A close agreement with the existing literature has been achieved for the efficiencies; hence, the experimental and calculation methods were reliable. The experiments in the millstream prove that the device was functioning well with efficiencies between 55.7 and 62.1%, which was comparable to the best performance recorded in literature for undershot water wheels (65%) [8, 9].

Table 7: Power and efficiency results from millstream experiments.

Parameters	Unit	Test 1	Test 2	Test 3
Average lifting speed	ms^{-1}	0.0679	0.0609	0.0613
Water speed	ms^{-1}	0.63	0.63	0.63
Water Density	$kg\ m^{-3}$	998	998	998
Area of paddles	m^2	0.713	0.713	0.713
Output Power	W	55	49	50
Water (input) Power	W	88.41	88.41	88.41
Efficiency	%	62.1	55.7	56.1

4.Conclusions

Waterwheels are eco-friendly and effective technology to harness energy from low flow water streams and therefore, may constitute an appropriate technology particularly in small city streams and rural irrigation canals. In this study, an undershot waterwheel (F-Gen) was designed, built and tested in swimming pool and millstream. Efficiencies of up to 69.7% and 62% were observed in the swimming pool and millstream experiments, respectively, which was an encouraging sign.

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